Noise Measurements of a Low-Noise Amplifier in the FDM Readout System for SAFARI

Qian Wang[1,2] · Michael D. Audley[1] · Pourya Khosropanah[1] ·
Jan van der Kuur[1] · Gert de Lange[1] · Amin Aminaei[1] · Dick Boersma[1] ·
Floris van der Tak[1,2] · Jian-Rong Gao[1,3]

Abstract
The SPICA-SAFARI instrument requires extremely sensitive transition edge sensor (TES) arrays with a noise equivalent power of 2×10^{-19} W/$\sqrt{\text{Hz}}$ and a readout system with an output noise that is dominated by the detector noise. It is essential to ensure the frequency domain multiplexing (FDM) readout system in SAFARI meets the noise requirement. The FDM system in SAFARI consists essentially of LC filters, a superconducting quantum interference device, a room-temperature low-noise amplifier (LNA), and a demultiplexer. Here we present a noise study of the LNA from a laboratory amplifier chain. We found the equivalent current and voltage noise of the LNA to be 5.4 pA/$\sqrt{\text{Hz}}$ and 315 pV/$\sqrt{\text{Hz}}$, respectively, which are low enough to read out SAFARI's TES arrays.

Keywords Transition edge sensor · Low-noise amplifier · Readout noise · SQUID

1 Introduction

SAFARI is a far-infrared (35–230 μm) spectrometer planned for the SPICA mission, which has a large (~2.5 m) and cold (~8 K) telescope [1]. Taking advantage of the low-temperature telescope with low emission, SAFARI is capable of detecting radiation in the sky-limited background, aiming to achieve an extraordinarily low-noise equivalent power (NEP) of 2×10^{-19} W/$\sqrt{\text{Hz}}$ [2]. SAFARI plans to use frequency domain multiplexing (FDM) to read transition edge sensor (TES) arrays [3]. Therefore, the key requirement of the readout system is that its noise should be lower than

✉ Qian Wang
  Q.Wang@sron.nl

1   SRON Netherlands Institute for Space Research, Groningen, Utrecht, The Netherlands

2   Kapteyn Astronomical Institute, University of Groningen, 9747 AD Groningen, The Netherlands

3   Faculty of Applied Science, Delft University of Technology, Delft, The Netherlands

the detector signal. The readout noise of the FDM system is expected to be dominated by the current noise of the SQUID and the noise of the LNA.

To evaluate the noise contribution from the LNA, we need to measure the current noise and the voltage noise of the LNA. Extracting these noise sources from the measured output noise is complicated because the output noise depends not only on these noise sources but also on the SQUID noise and the loading impedance at the input of the amplifier, both of which are determined by the SQUID settings. So we need to measure the noise of the LNA separately. This paper reports the output noise of the LNA measured with different resistors ranging from 10 to 400 Ω at different temperatures (50 mK and 1.3 K) at the input. The current noise and voltage noise of the LNA are estimated from the fitting of the measurements with a noise model. To verify the fitting parameters, a room-temperature open- and shorted-circuit measurement is also taken.

2 Measurement Setup

The LNA used is homemade and is part of an SRON front-end electronics (FEE), which has 74-dB gain in the range 1–5 MHz and active input impedance for impedance match. The SQUID in our study is a single-stage PTB (The National Metrology Institute of Germany) SQUID which contains 16 SQUIDs array. The load resistors are placed in the mK stage of a Leiden Cryogenics (LC) dilution cooler and are connected with the LNA via a loom that goes from the top of the cooler to its bottom [4, 5]. The load resistors are introduced to replace the SQUID, to simulate the dynamic impedance of the SQUID. In this way, there is no current noise contribution of the SQUID, and we can measure LNA noise contribution with a set of representative interface. As illustrated in Fig. 1, there are 10 load resistors on a homemade printed circuit board (PCB). By connecting a different load resistor, we can simulate different load impedances of the SQUID at the input of the LNA. The measured output noise consists of the voltage noise and the current noise of the LNA, which are the aim of this work, and also the Johnson thermal noise from both the load resistors and the loom.

3 Noise Measurement Results and Analysis

3.1 Offset Noise of DEMUX

In our FDM system, the DEMUX is used not only to provide a digital-to-analog converter (DAC), which supports the 1–4-MHz AC bias to TESes, but also has an analog-to-digital converter (ADC), which records the readout noise [6]. Hence, it is important to do a measurement first to quantify the noise from the DEMUX. The measurement can be realized by varying the high-frequency (HF) gain from the LNA.

If the noise from the DEMUX is zero, one could measure zero readout noise with the zero gain, but if there is a certain noise from the DEMUX, there will be an offset
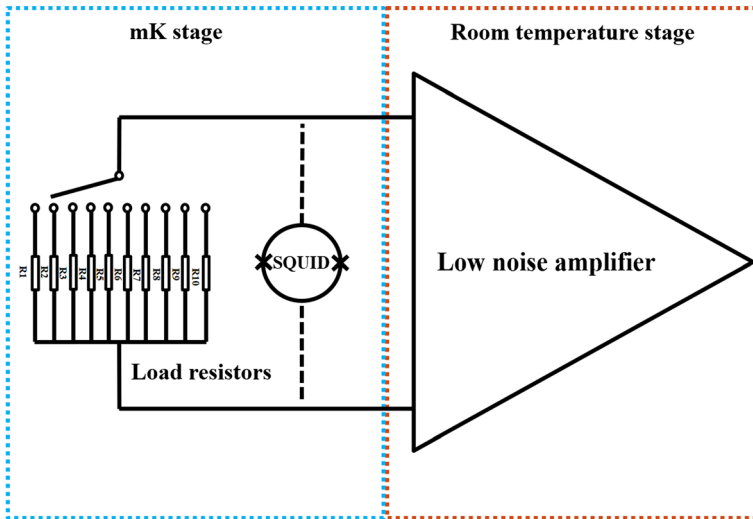
Fig. 1 Simplified circuit scheme between the LNA and the load resistors. The latter range from 10 to 400 Ω and are placed in the mK stage to simulate the SQUID. The dashed line means the SQUID is not connected. (Color figure online)

noise when the gain approaches zero. Figure 2 shows our measured readout noise as a function of the high-frequency (HF) gain of the LNA. The offset noise of the DEMUX is seen to dominate when the HF gain is lower than 1000. The offset noise is 173 ± 1 nV/$\sqrt{\text{Hz}}$ in our case. The noise data are obtained from the readout noise averaged in the range of 1 to 2 MHz, to be of interest in our FDM study. The fitted lines to the low-temperature (1.3 K) and higher-temperature (4 K) data of load
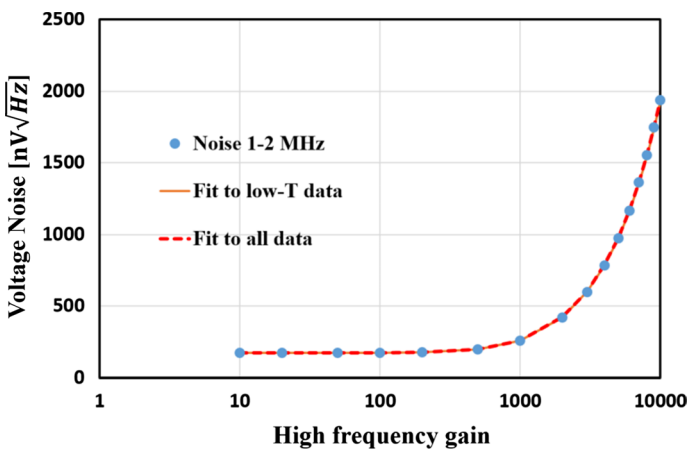

Fig. 2 Measured noise versus the HF gain, plotted on a logarithmic scale. The offset noise value of the DEMUX is 173 nV/$\sqrt{\text{Hz}}$. The measured noise depends linearly on the high-frequency (HF) gain when the gain is larger than 1000. (Color figure online)

resistors are identical within ± 1 nV/$\sqrt{\text{Hz}}$ error. Because of this offset noise, we always set the HF gain higher than 1000. Since we use a 2:1 transformer, the real gain is a factor of two lower than the setting gain.

3.2 Noise Results and Model

Noise measurements of the LNA are performed under an open-loop condition (without feedback in the warm electronics) with the load resistance at 50 mK or 1.3 K, respectively. During these measurements, we change the value of the input impedance R_{in} for the LNA, which has a value of 40, 50, 70, 88, 109, 129 Ω. The LNA noise consists of a voltage noise V_{n} and a current noise I_{n}.

The practical scheme of the LNA is rather complex, but we simplify it by modifying a common noise model [7] to calculate its noise, which is shown in Fig. 3. According to this noise model, the noise of the DEMUX is independent of the HF gain and increases the total readout noise level, so the V_{DEMUX} contributes an offset of the readout noise. Both the current noise and the voltage noise of the LNA, as well as the Johnson noise from the source resistance R_{s}, are amplified by the HF gain. The R_{s} consists of the load resistance and the resistance of the leads in the loom, both of which are known. One complication of R_{s} is that the load resistor and the electrical leads in the loom are at different cryogenic temperatures. So, the Johnson noise of the load resistor and the leads should be dealt with at two temperatures. The Johnson noise from input impedance can be negligible because it is not amplified by the LNA. This leads to Eq. (1) to derive the LNA noise:

$$V_{\text{measured}} = \sqrt{V_{\text{DEMUX}}^2 + \text{Gain}^2 \cdot \left[\left(I_{\text{n}}^2 \cdot R_s^2 + V_{\text{n}}^2 + 4 \cdot k_{\text{B}} \cdot T \cdot (R_s - R_{\text{lead}}) + 4 \cdot k_{\text{B}} \cdot T_{\text{lead}} \cdot R_{\text{lead}} \right) \cdot \left(\frac{R_{\text{in}}}{R_{\text{in}} + R_s} \right)^2 \right]}$$
(1)

where k_{B} is the Boltzmann constant, T is the temperature of the load resistance, and T_{lead} is the average temperature of the leads. When it is not at room temperature, the average temperature of the leads is 100 K, as estimated from the different lengths in different temperature stages.
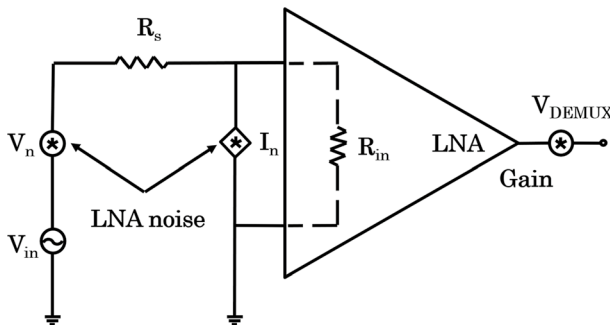

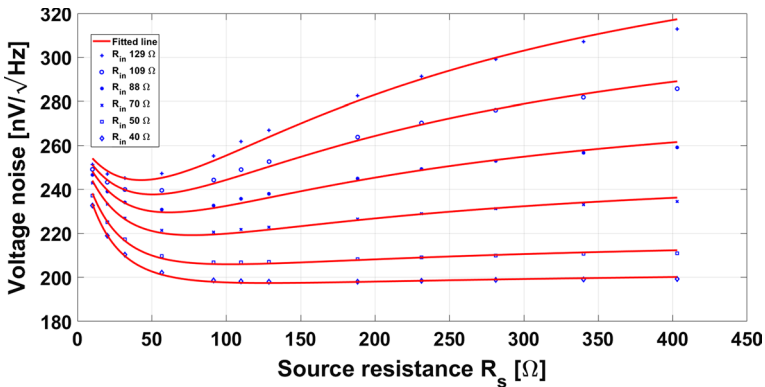**Fig. 3** Simplified noise model for the LNA. A current noise source and a voltage noise source are considered

Fig. 4 At 50 mK, output noise as a function of R_s with different R_{in}. The fit line corresponds to R_{in} ranging from 40 to 129 Ω. The data measured at 50 mK fit well with the noise model by modifying the value of the current noise and voltage noise of the LNA. The fitted current noise is 5.4 pA/$\sqrt{Hz}$, while the fitted voltage noise 315 pV/$\sqrt{Hz}$. (Color figure online)
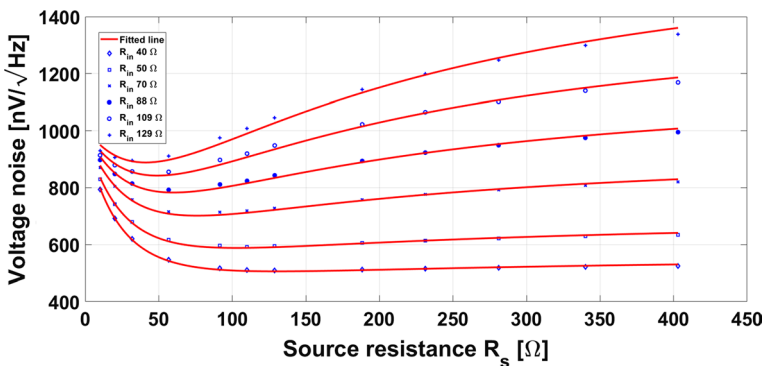

Fig. 5 At 1.3 K, the output noise as a function of R_s with different R_{in}. The fitted current noise is 5.4 ± 0.1 pA/$\sqrt{Hz}$, while the fitted voltage noise 315 ± 10 pV/$\sqrt{Hz}$, both identical to the fitted parameters at 50 mK. (Color figure online)

3.3 Fit Line of the Measured Output Noise at 50 mK and 1.3 K

We plot the measured voltage noise versus source resistance at 50 mK (HF gain 1000) and 1.3 K (HF gain 5000) in Figs. 4 and 5, respectively, together with the fits using Eq. (1). The different gain values are chosen to test whether the equation holds for various gain settings. The current noise and voltage noise are the fitting parameters. The best fits in Fig. 4 give the current noise and voltage noise of the LNA to be 5.4 ± 0.1 pA/$\sqrt{Hz}$ and 315 ± 10 pV/$\sqrt{Hz}$, respectively.

The best fits in Fig. 5 illustrate the identical (within the uncertainty) current noise and the voltage noise of the LNA as what we found from 50 mK data, confirming the model. Thus, we have now derived the noise data of our LNA.

3.4 Open and Shorted Measurement at Room Temperature

Either an open- or shorted-circuit room-temperature measurement is taken to verify the noise model (HF_gain 5000). The fitted current noise and voltage noise of the LNA are 5.4 pA/$\sqrt{\text{Hz}}$ and 303 pV/$\sqrt{\text{Hz}}$, as illustrated in Fig. 6.

The current noise estimated from the fit of the open-circuit measurement is identical to the LNA noise extracted from the low-temperature measurements. However, the fitted voltage noise has a 10 pV/$\sqrt{\text{Hz}}$ difference with the estimated voltage noise, which is probably due to the nonzero resistance in the shorted circuit and a systematic error in the estimation of the cable noise contribution.

3.5 Noise Temperature of LNA and SQUID Noise

The noise temperature of the LNA can be calculated by Eq. (2):

$$T_{\text{n}} = \frac{\left(V_{\text{n}}^2 + I_{\text{n}}^2 \cdot R_{\text{s}}^2\right)}{4 \cdot k_{\text{B}} \cdot R_{\text{s}}} \tag{2}$$

Using the voltage noise and current noise estimated from the fitted lines and the R_{s} of 100 Ω (~ SQUID transresistance), the noise temperature of the LNA is 80 K.

As described in [8], the readout noise referred to the input of the SQUID is about 18 pA/$\sqrt{\text{Hz}}$, depending on the operating conditions and on the presence of the LC filters. The estimated current noise of the SQUID corresponds to approximately 100 Ω SQUID transresistance at a few K; thus, the noise of the readout is dominated by the LNA noise. If we use relatively slow (time constant ~ 40 ms) TES devices and bias them to the low-transition region, the output noise of the TES will be well above the noise of the readout.
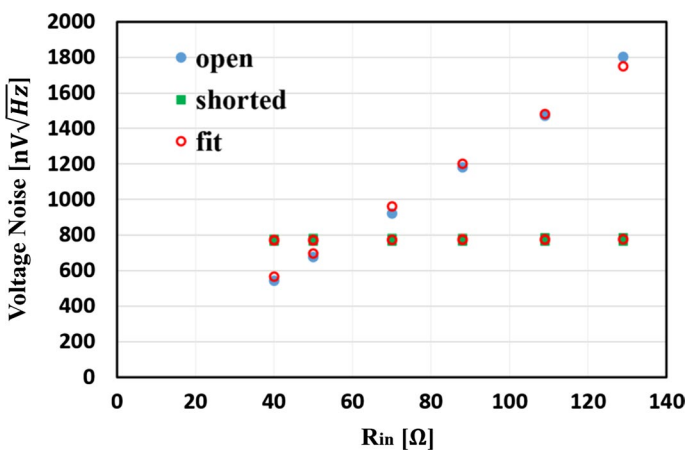

Fig. 6 Readout noise as a function of input impedance in open- and shorted-circuit measurement at room temperature. The resistance of open and shorted circuit is about 3 MΩ and 0.5 Ω, respectively. The fitted current noise is 5.4 pA/$\sqrt{\text{Hz}}$ and voltage noise 303 pV/$\sqrt{\text{Hz}}$

4 Conclusion

The noise measurements of the LNA can be well explained with a simple noise model with equivalent noise sources as fitting parameters. The extracted current noise and the voltage noise of the LNA are 5.4 pA/$\sqrt{\text{Hz}}$ and 315 pV/$\sqrt{\text{Hz}}$, respectively. The noise temperature of the LNA is 80 K with 100 Ω resistance. The offset voltage noise of the DEMUX is 173 nV/$\sqrt{\text{Hz}}$. We found that the noises of the LNA are low enough to read out SAFARI's TES arrays.

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